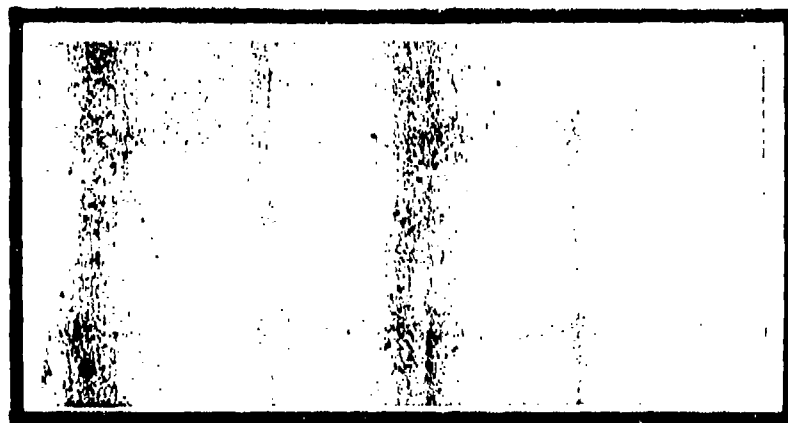


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A SYSTEM SIMULATION OF THE EXECUTION
OF SCHEDULED MAINTENANCE AT A
MINUTEMAN MISSILE WING

Norman B. McAlpin, Captain, USAF
Lawrence J. Vaccaro, Jr., Captain, USAF

LSSR 24-82

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Minuteman Missile maintenance is performed in a highly dynamic and complex environment. Strategic deterrence depends in part on the capability of the maintenance organization to be responsive to this environment. However, maintenance efficiency is also important. Scheduling effectiveness is a primary measure of this efficiency. Scheduling effectiveness is the ratio of workorders completed to workorders scheduled. Deviations occur which prevent scheduled workorder completion. These are either controllable by wing level managers, or uncontrollable. The primary controllable factor is personnel error. This research focuses on the determinants of scheduling effectiveness, and the possible effects of management action to reduce the number of controllable deviations. Wing level source data is examined, and a Q-GERT simulation is developed. Sensitivity analysis is performed on the model. Two independent variables, personnel error and vehicle and equipment problems, are varied and the resulting effect on the scheduling effectiveness rate is measured. Using the assumption that equal levels of management attention will produce equal percentage reductions in the incidence of personnel errors and vehicle and equipment deviations, the model shows that the personnel error factor has the greater impact on scheduling effectiveness. Several insights are presented along with recommendations for facilitating further research in this area.

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A SYSTEM SIMULATION OF THE EXECUTION OF
SCHEDULED MAINTENANCE AT A
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A Thesis

Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology
Air University

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Logistics Management

By

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September 1982

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and

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has been accepted by the undersigned on behalf of the faculty of the School of Systems and Logistics in partial fulfillment of the requirements for the degree of

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CHAPTER 1

INTRODUCTION

United States strategic deterrence rests upon the existence of a combined nuclear force consisting of air, sea and land forces. This combined force is known as the strategic triad (MX Missile System, 1979:25). The landbased segment of this triad currently consists of Minuteman and Titan Intercontinental Ballistic Missiles (ICBMs). Of the two, Minuteman missiles outnumber the Titan force by a ratio of approximately 20 to one. In order to provide maximum deterrent capability, these missiles must be kept in a high state of readiness (Connell and Wollam, 1968:1; Grimard, 1980:306). An individual missile is said to be "on-alert" if it exists in a state of readiness; hence, a high proportion of on-alert missiles (high alert rate) is desirable.

Proper maintenance of the Minuteman Missile force is required in order to sustain a high alert rate, and this fact is recognized by the Department of Defense (DOD) (Connell and Wollam, 1968:1). The Air Force, as a DOD component, is responsible for the efficient management of the Minuteman Missile force. The ultimate goal of ICBM maintenance management, and in particular Minuteman Missile maintenance, (henceforth referred to as Missile Maintenance) is a high level of support for the Single Integrated

Operations Plan (SIOP) (Grimard, 1980:306), which is "America's strategic nuclear strike plan," (Collins, 1980: 58). This high level of support must, however, be achieved at the lowest possible cost, and with the highest regard for equipment and personnel safety (SACR 66-12, 1981a:1-1,1-2; Grimard, 1980:285).

The Strategic Air Command (SAC) is the Air Force operational command responsible for the Minuteman Missile force. Official SAC ICBM maintenance policy is stated in SAC Regulation 66-12 as follows:

. . . a high alert rate is required; however, it must be the product of effective and safe management of assets without compromise of safety, security or maintenance discipline [1981a:1-1].

The regulation also states that "maintenance resources should be committed on a scheduled basis to permit effective planning actions that will enhance maximum maintenance [1981a: 1-2]." U.S. Air Force Manual (AFM) 66-1 refers to maintenance scheduling as "the key to efficient use of resources [1980:A3-2]." Therefore, if scheduling of maintenance activities is desirable, then it follows that some measure of the effectiveness of the schedule would be an important management tool.

The effectiveness of a given schedule can be measured in a variety of ways. Chase and Aquilano (1981:434) mention "satisfactory completion of the jobs (scheduled), utilization of the productive facilities, and meeting of the organization's overall objectives" as three of the possible

evaluation methods. Another such measure (and one commonly used in the Air Force) is Scheduling Effectiveness. This is defined by SACR 66-12 as the "ratio of items committed to the daily or weekly maintenance plan to those items completed on the date indicated [1981:A5-7]." Scheduling effectiveness, as used in missile maintenance organizations, contains aspects of the three methods mentioned, but at the same time completely encompasses none of them.

Satisfactory job completion is generally implied by the completion of a given workorder. However, scheduling effectiveness is an aggregate measure of the degree to which all jobs were successfully completed, and is thus not quite the same thing.

Scheduling effectiveness also implies the degree to which a maintenance organization's productive facilities are utilized. However, in and of itself, the scheduling effectiveness rate provides an incomplete measure of this utilization. For example, a scheduled workorder may not be completed because the resources allocated to that job were required for a more important, (higher priority) but unscheduled job. Here, the productive facilities (equipment resources in this case) were utilized, but the scheduling effectiveness rate alone would not indicate this fact.

Scheduling effectiveness also provides some indication of the degree to which organizational objectives (scheduled maintenance for example) are met. Yet, there are

other organizational objectives (e.g., a high alert rate) which are of equal or (in this case) greater importance. Attainment of these objectives is not apparent in the scheduling effectiveness rate.

Although the scheduling effectiveness measure alone does not provide a complete picture of the effectiveness of maintenance resource utilization (SACR 66-12, 1981a:A5-7), it can provide significant insight into the overall maintenance effort within a particular organization. Therefore, assuming that this measure is useful, and assuming that high values of scheduling effectiveness are generally preferable to lower values, then an examination of the individual factors which determine scheduling effectiveness is important.

Currently, missile maintenance managers receive periodic analysis reports on various aspects of their organization's maintenance activities. This includes scheduling effectiveness data. This data provides a breakdown--by number of occurrences and general reason--of the number of scheduled jobs not completed during the applicable period. While this data provides some insight into maintenance and related problem areas, it does not necessarily indicate the areas to which scheduling effectiveness is most sensitive. Further, the various factors may exhibit interactions that are not apparent in the reports. Given that a manager desires to improve scheduling effectiveness, in

which area could management action, and limited resources, yield the greatest improvement?

Background

In order to more clearly understand maintenance scheduling effectiveness, a general understanding of the conditions under which this maintenance is performed is essential. This section will provide a brief explanation of the environmental and organizational characteristics pertinent to Minuteman maintenance.

Minuteman Missiles are housed in reinforced, unmanned, underground silos. These silos are geographically separated from one another and are deployed in the states of Missouri, Montana, North and South Dakota, and Wyoming. Maintenance personnel are dispatched from a central location in response to existing maintenance requirements. These requirements are discovered in one of two ways. First, all missiles are electronically monitored by a launch crew responsible for a given set of missiles. Upon receipt of a malfunction report from a particular missile's computer, the problem would be reported by the crew to an agency known as Maintenance Control (described later). The second means for detecting problems is through physical observation by maintenance teams that are on-site for periodic inspections or other maintenance.

The dispatched technicians travel by truck to the various missile locations in order to perform maintenance,

and several factors can prevent this maintenance from being accomplished. Among these factors are vehicle breakdowns, and numerous conditions attributable to the severe weather frequently encountered in the Western and Great Plains areas. Another factor which must be considered is time. One-way travel times (in good weather) to the silos range between approximately an hour (for the closer silos) to several hours (for the more distant sites). This can severely limit the amount of maintenance which can be performed in a single workshift. For example, maintenance teams that perform maintenance at missile sites are generally limited by regulation to a maximum duty shift of 16 hours (for safety reasons). In order to place the time limitation factor in proper perspective, an "average" workshift will next be described.

A workshift begins when a team initially reports for duty. The first things the team must do are collectively referred to as pre-dispatch activities. These primarily consist of vehicle and equipment checkout and various crew briefings. Next comes the actual drive to a missile site. This can be conservatively estimated, on the average, to be two hours (in good weather). Upon arrival at the site, special entrance procedures must be followed. These procedures, and formidable mechanical barriers, are such that a maintenance crew is fortunate if it can completely "penetrate" (gain access to the below-ground silo area) a site

within one hour after arrival. After penetration, equipment set-up can take anywhere from minutes to hours depending on the maintenance to be performed. Forty-five minutes could be considered "average". At this point, the crew has been on duty for nearly six hours (commonly referred to as the crew members being six hours "into their timeline") and still has not performed any maintenance.

Upon completion of its maintenance, the crew will basically perform all pre-maintenance tasks in reverse. Post-maintenance time is usually slightly less than pre-maintenance time, and in the hypothetical situation described can be estimated at five hours. Therefore, of the total allowable workshift time of 16 hours, only five hours might be available for actual maintenance. This latter time could be extended by having the maintenance team remain overnight (RON) at an Air Force lodging facility close to the respective missile site. However, for various reasons (which will not be examined here), it is often desirable to have the team, and its assigned equipment, return to the point of origin.

Security is yet another ever present factor (SACR 66-12, 1981a:1-1,4-1). For example, armed security guards must accompany missile maintenance personnel whenever penetration is required. Since a substantial amount of on-site maintenance requires access to the below-ground silo area,

a lack of sufficient security personnel can severely limit the maintenance which can be accomplished.

Still another problem involves support of maintenance teams while they are at the silos. If maintenance equipment fails or additional parts are required, these must be delivered either by helicopter or surface vehicle. Weather problems (e.g., extremely high winds or icy roads) and time often preclude this support, thus preventing the completion of a particular job on the date scheduled.

Turning next to organizational considerations, maintenance production is controlled by a centralized resource allocation agency known as Maintenance Control (SACR 66-12, 1981b:1-1). Within Maintenance Control, the Scheduling Control branch "plans and schedules the expenditure of resources to accomplish known maintenance requirements . . . [SACR 66-12, 1981b:2-1]." Scheduling Control plans overall job requirements and then converts these planned jobs into scheduled jobs which appear in weekly and daily maintenance plans. These plans "merge specific actions [job requirements] with specific resource assets [SACR 66-12, 1981b:2-4]." This process of merging jobs with assets deserves a closer look.

The weekly and daily maintenance plans (schedules) are finalized at, respectively, weekly and daily planning meetings. At each of these meetings, "every agency which has an ICBM maintenance performing or supporting

responsibility must be represented [SACR 66-12, 1981b:2-3]."

The personnel who attend these meetings "must be qualified and authorized to make firm commitments of their agency's resources [SACR 66-12, 1981b:2-3]." Further, upon completion of either meeting, "there should be a joint understanding as to what the requirements are, who is expected to support them, and when and where they are to be done [SACR 66-12, 1981b:2-3 to 2-4]." These meetings consume the time and effort of numerous individuals in the scheduling of maintenance resources. If the jobs are not accomplished as scheduled, then the time and effort expended in planning and scheduling those jobs is essentially wasted. Furthermore, the jobs will then have to be replanned and rescheduled.

The manpower necessary to accomplish the scheduled jobs is assigned to maintenance squadrons on a permanent basis. The squadrons have administrative and supervisory control over their assigned personnel and provide their services to Maintenance Control for limited periods of time. While accomplishing their scheduled or assigned maintenance jobs, these personnel are under the direct control of Maintenance Control. Upon completion of their jobs, supervisory control reverts back to the maintenance squadrons.

Maintenance personnel perform assigned maintenance jobs in teams. These teams are organized based upon specialized abilities, and team member substitution between specialties is rarely possible. Hence, the available

manpower pool is segmented into several sub-pools (branches and shops), each capable of providing a finite number of work teams (SACR 66-12, 1981a:1-1,1-4).

Task requirements are stringent due to the nature of missile maintenance (nuclear and explosive safety, security, etc.), and normally an entire homogenous team is required before a given job can be performed. The significance of this is that the loss of one member of a five person team, for example, can often cause a job to be cancelled, even though additional personnel from other branches may be available, since they are not qualified for the task.

Problem Statement

An examination of maintenance analysis data regarding scheduled workorder completion rates for four operational Minuteman maintenance organizations shows that approximately 20 percent of all scheduled, on-site maintenance tasks are not completed (44th Strategic Missile Wing, 1981:7; 321st Strategic Missile Wing, 1980:C9; 341st Strategic Missile Wing, 1981:3; 351st Strategic Missile Wing, 1981:4-3). The reasons for noncompletion are varied, but can be roughly divided into "controllable" and "uncontrollable" categories based upon whether the causal factors are considered to be amenable to local management action.

Examples of uncontrollable deviations include problems caused by severe weather, random missile system failures of an urgent nature which require diverting scheduled

resources, and higher headquarters directed changes. Problems such as these are constraints within which a maintenance manager must work; they are assumed to be beyond local managerial control.

Controllable deviations on the other hand are considered to be susceptible to immediate managerial attention. Problems of this type can include (to a degree) vehicle and equipment availability and serviceability, and deviations caused by personnel error. While problems of this type are not completely controllable (because of their random component) it is assumed that they are controllable to a certain extent. And this is important because a substantial number of incomplete tasks are due to controllable deviation factors. However, while these factors are amenable to management attention, managerial time is a finite, much demanded resource. Expending managerial resources in one area frequently means that managerial resources must be withdrawn from another (hopefully) less important area. Given that this resource is scarce, it must in turn be managed for greatest effectiveness. The problem then, is to discover those determinants of scheduling effectiveness which are most susceptible to increased management attention.

Given that scheduled maintenance leads to the most efficient (and hopefully, effective) utilization of maintenance resources (manpower, parts, equipment, vehicles, etc.), and that scheduling effectiveness is a measure of this

utilization, any controllable factors which decrease scheduling effectiveness are important. This research will focus on Minuteman maintenance scheduling effectiveness in general, with particular attention to those controllable factors which decrease scheduling effectiveness.

CHAPTER 2

LITERATURE REVIEW

Most authors and researchers agree on the essential elements and objectives of maintenance. One general definition with which most researchers would not disagree is, "the task of caring for material items through servicing, inspection, repairing, modifying or overhauling [Peppers, 1981:105]." Air Force Regulation (AFR) 66-1 clearly defines the USAF maintenance program:

Maintenance, as a functional element of the organization, is responsible for ensuring that Air Force material is serviceable, safely operable, and properly configured to meet the mission needs. This is done by performing maintenance which includes, but is not limited to, inspection, repair, overhaul, modification, preservation, testing, and condition or performance analysis [1980:1-1].

The recent highly inflationary economy combined with recurring defense budget constraints has put severe pressure on Air Force maintenance organizations to operate at higher levels of efficiency and effectiveness. This pressure is reflected in the writings of logisticians and policy makers (AFR 66-14, 1978:61; Toner, 1981:3; Peppers, 1981:105; Kane, 1981:20). "Mission performance at the least possible cost" is a common phrase in the literature (Grimard, 1980:285; AFR 66-14, 1978:2). Gorby (1981:18) explains that the benefits of efficiency are in that money or resources

not used in one task can be used to do other tasks that were not being done because of lack of resources. Peppers writes that "the actions, deliberations, and decisions of a manager should be aimed at the efficient use of resources to effectively accomplish his specific goals [1981:108]."

Kane (1981:20) notes that with a total annual maintenance cost well in excess of five billion dollars, the Air Force could realize tremendous savings through improved maintenance procedures. Peppers (1981:145) points out that efficient maintenance is important to national defense because it is a primary determinant of military capability.

The issue of efficiency in the utilization of resources is also reflected in official DOD and USAF publications and directives. According to Wyatt (1981:171), DOD Directive (DODD) 4151.6 states that the objectives of equipment maintenance are:

. . . to sustain weapons and equipment and systems in a state of operational readiness consistent with the mission requirements of the operating or tactical elements, and at the least total cost [1981:48].

Air Force Manual (AFM) 400-2, Air Force Logistics Doctrine (1968:3-4,4-6), calls for skillful and prudent use of logistics resources to enable the Air Force to accomplish its mission with minimum expenditure of resources. Additionally, AFM 400-2 (1968:3-4,4-6) outlines the philosophy that every opportunity must be taken to reallocate resources to increase total benefits and to reduce life cycle maintenance costs.

One widely recognized method of reducing maintenance costs is through the proper use of planning and scheduling techniques. Newbrough (1967:137) describes the purpose of scheduling as the pledging of all required maintenance resources far enough in advance to achieve maximum support of the production effort. He believes that scheduling provides for the orderly and economical accomplishment of jobs. Peppers writes that "many advantages accrue to the unit when planning obligations are soundly met. The most obvious is the orderly and purposeful application of effort [1981:153]." Grimard notes that support of the SIOP "requires high alert rates and, therefore, near perfect execution of work scheduling, control, and performance [1981:307]."

The importance of scheduling is also recognized in Air Force maintenance directives. AFR 66-1 directs that maintenance be done on a preplanned, scheduled basis when possible. It further states that:

Proper planning provides supervisory personnel with the workload plans needed for the efficient use of personnel, facilities, and equipment. Proper planning reduces unscheduled maintenance and allows for an orderly progression of maintenance actions toward returning material to a safe and operable condition [1980:1-1].

In addressing the Air Force manager's planning responsibilities, AFR 66-1 describes scheduling as an important element of those responsibilities. It describes proper scheduling as "the key to efficient use of resources," and therefore absolutely essential for ensuring that required actions are

precisely scheduled and that the schedules are met (1980: 3-2).

Strategic Air Command Regulation (SACR) 66-12 spells out the command's policy for the scheduling of missile maintenance. The policy stresses efficiency in the utilization of resources and explains that scheduling is the key to "effective planning actions that will enhance maximum maintenance production [1981a:1-2]." The regulation also directs that "unscheduled commitment of maintenance resources should be the exception and held to a minimum [1981a:1-2]."

Past research pertaining to scheduling methodologies has been applied to a wide variety of situations. The scheduling technique that an organization uses is highly dependent on the overall production requirements for the organization (Chase and Aquilano, 1981:425-426). For example, linear programming can be used to schedule the optimum quantity and mix of primary materials in continuous processing situations (Chase and Aquilano, 1981:426,447). Program Evaluation and Review Technique (PERT) and Critical Path Method (CPM) are two useful methods for determining the critical path of sub-task completion in a project situation (Chase and Aquilano, 1981:553). Linear programming can also be used to assign jobs to machines or people to jobs in a job shop situation (Chase and Aquilano, 1981:438). Yet another job shop scheduling technique is Johnson's rule. This technique yields an optimal solution when two or more

jobs must be processed on one or two machines in a job shop situation (Chase and Aquilano, 1981:435).

Scheduled maintenance in a missile maintenance organization has many characteristics which are similar to the classical job shop situation if one considers that maintenance requirements correspond to orders and required maintenance tasks are considered to be mini-projects (Chase and Aquilano, 1981:429). As in a job shop, production routing is separately developed for each work package, separate records are kept for each package, and the progress of each work package is separately monitored (Chase and Aquilano, 1981:429-430).

However, the complexity of scheduled missile maintenance is considerably greater than the typical job shop production situation. This complexity is a result of several different factors. First, there are a wide variety of jobs which may have to be accomplished on any given day. Second, the number of people and pieces of equipment available to accomplish these jobs varies from day to day. Additionally, other considerations such as security or weather can have a tremendous impact on the scheduling and accomplishment of maintenance. All of these factors would seem to preclude the efficient and effective use of classical job shop scheduling techniques for missile maintenance.

All of the previously discussed scheduling techniques use a systematic approach to the scheduling of jobs. Indeed,

the use of any consistent methodology implies a systematic approach to the process. Perhaps scheduling effectiveness may be more clearly understood if it is viewed from a systems perspective. In other words, from a viewpoint which envisions scheduling effectiveness as part of a larger entity or "whole" (Schoderbek et al., 1980:6), thereby including the relationships between scheduling effectiveness and its determinants. One definition of a system is:

. . . a set of objects together with relationships between the objects and between their attributes connected or related to each other and to their environment in such a manner as to form an entity or whole [Schoderbek et al., 1980:12].

A brief discussion of the key components of this definition is in order.

According to Schoderbek et al., "objects are the components of a system [1980:14]." Functionally speaking, these parts are the input(s), the process(es), the output(s), and the feedback control. System inputs "are the start-up force that provides the system with its operating necessities [Schoderbek et al., 1980:14]." The same authors describe a process as "that which transforms the input into output [1980:18]." System outputs, then, are "the purpose for which the system exists [Schoderbek et al., 1980:18]." Finally, feedback control is a system output that is used as an input to that same system for control purposes (Schoderbek et al., 1980:17).

The above authors also define relationships, attributes and environment. Relationships "are the bonds that link the objects together [1980:19]." Attributes are "properties of objects and of relationships ... [that] ... manifest the way something is known, observed, or introduced in a process [1980:21]." Environment is that which is "beyond the system's control ... [but which exerts a] ... significant determination on the system's performance [1980:22]."

A diagram of the Schedule Execution System is shown in Figure 2-1. The system uses the output of the scheduling system as one input, and controllable and uncontrollable deviation factors as its remaining inputs. The process is schedule execution, and system outputs include complete and incomplete workorders and the scheduling effectiveness rate. The latter is used as feedback into the scheduling process (to influence various management decisions). The former two outputs either add to or subtract from the workload requirements input to the scheduling process.

One point which deserves mention and is apparent in Figure 2-1, is that feedback is not used within the Schedule Execution System. Instead, a portion of its output is fed back to the Scheduling System. Hence, the figure is a departure from the definition of a system presented earlier. Schoderbek et al. (1980:70) refers to systems wherein system output is not used as (some) system input as "open loop systems."

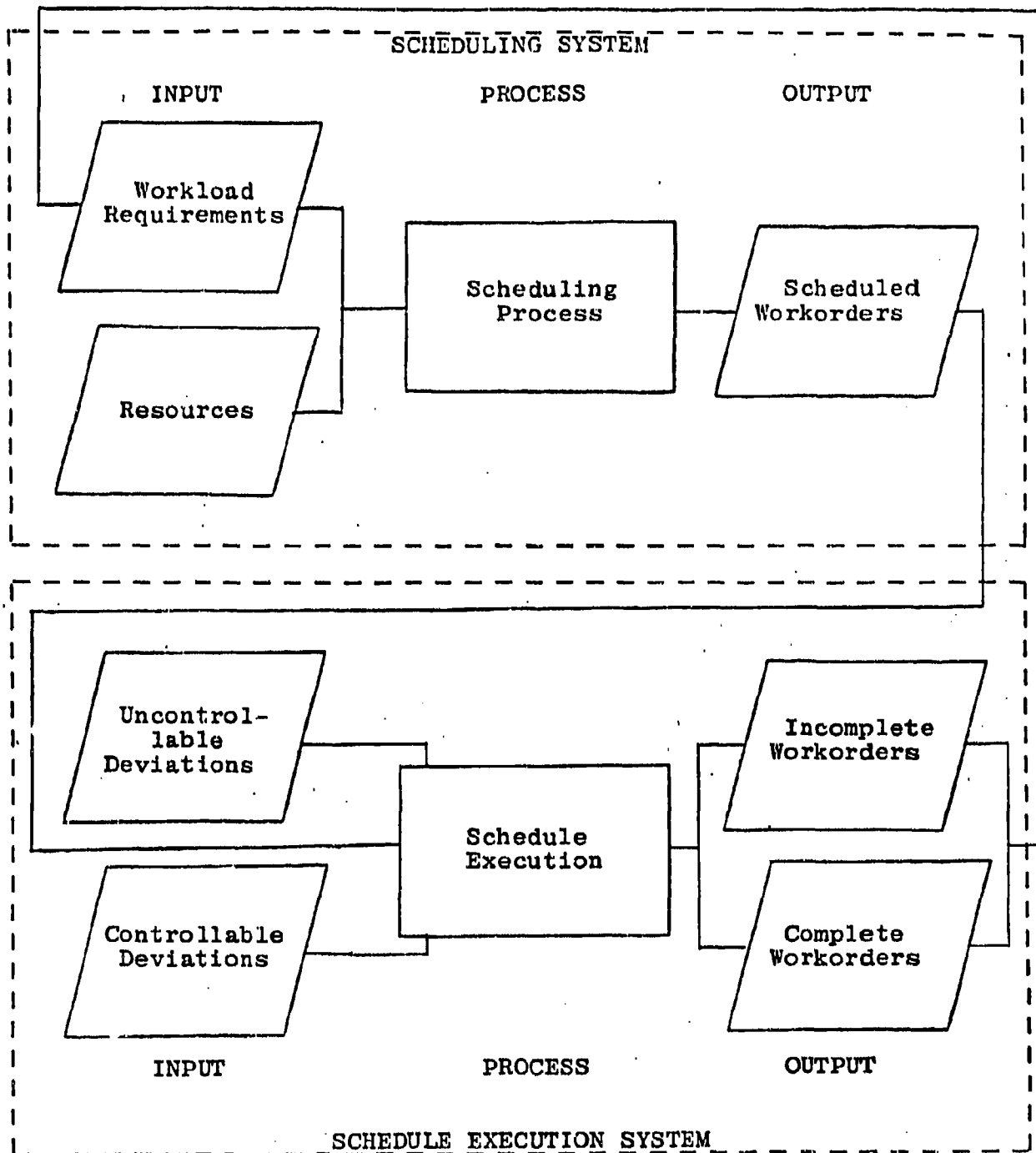


Figure 2-1. Scheduling Systems Interaction

According to Niland (1970:53), the first requirement of a scheduling system is an explicit description of work requirements. Based on these requirements, he writes that a scheduling system should have four basic features. These are:

1. A measure of plant capacity available.
2. A measure of capacity needed to accomplish the required work.
3. A systematic method of allocating the available capacity to the jobs being scheduled.
4. A method and a cycle for rescheduling incomplete jobs [Niland, 1970:53-55].

Thus, scheduling systems characteristically concentrate on obtaining an optimum match of resources with workload requirements. This optimization goal also holds true for a missile maintenance organization. However, scheduling systems generally do not address the underlying factors which determine capacity and workload requirements. For example, in a missile maintenance organization, vehicles, equipment, personnel and security requirements are all primary determinants of maintenance capacity. These factors cause available capacity to have probabilistic instead of deterministic characteristics. This probabilistic characteristic renders any certain measurement of capacity virtually impossible. Additionally, workload requirements can change drastically because of high priority system failures.

If one assumes that the scheduling function accomplishes its optimization goal with the current information available to it, then scheduling effectiveness is not only

a function of the work scheduling technique, but also of the probability that the system will not change from the time the schedule is published until the time the schedule is executed. Scheduling effectiveness is, therefore, based on management's ability to control the factors which determine workload requirements and available capacity.

There are several methods available for the study of dynamic systems such as the missile maintenance Schedule Execution System. One method is the field study which involves direct experimentation on the system. Shannon notes that this technique avoids the necessity for validating a model; however, it has several distinct disadvantages. These disadvantages are:

1. It could disrupt organization operations.
2. If people are an integral part of the system . . . the fact that people are being observed may modify their behavior.
3. It may be very difficult to maintain the same operating conditions for each replication or run of the experiment.
4. It may be more time-consuming and more costly to obtain the same sample size
5. It may not be possible to explore many types of alternatives in real life experimentation [1975:11].

It would appear that all five of these disadvantages apply to the execution of a missile maintenance organization's maintenance schedule and therefore would render direct experimentation infeasible.

Another method for predicting outcomes of a system as a function of the inputs is regression analysis (McClave and Benson, 1979:337). A good regression analysis model can

provide relatively accurate estimates of a dependent variable based on the relationship between that dependent variable and certain independent variables derived from an historical sample (McClave and Benson, 1979:336,337). However, values of the independent variables outside the range of the sample can give misleading and inaccurate results (McClave and Benson, 1979:348). Thus, regression analysis lacks the capability to use probability distributions as inputs for the independent variables.

Another powerful and popular method of predicting the outputs of a system based on probabilistic inputs is computer simulation (Shannon, 1975:ix). One reason for the popularity of computer simulation is its adaptability to complex and dynamic systems. Often, computer simulation (with operator induced input changes) is the only analysis technique which provides the level of sophistication needed for complex systems (Schoderbek et al., 1980:293).

Shannon defines simulation as:

. . . the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies for operation of the system [1975:2].

Most other authors propose similar definitions (Lehman, 1977:4-5; Gordon, 1969:17-18; Emshoff and Sisson, 1970:8). Shannon suggests that simulation be considered when one or more of several situations exist. Two of these conditions which seem to exist for the current problem are:

1. It is desired to observe a simulated history of the process over a period of time in addition to estimating certain parameters.

2. Simulation may be the only possibility because of the difficulty in conducting experiments and observing phenomena in their actual environment . . . [1975:11].

Additionally, Fishman (1978:4) notes that simulation allows the investigator to identify and control sources of variation by controlling the input parameters of the system.

The Rand Corporation conducted several simulation studies of ballistic missile maintenance and scheduling policies during the early 1960s. One study (Jorgenson et al., 1963) specifically addressed missile and missile component scheduled maintenance and replacement policies. Another study (Bean and Steger, 1960) presented a simulation which generated random maintenance and supply requirements for an ICBM unit. Yet another study (McCall, 1962) presented a method for updating missile recycle policy as additional malfunction and performance data becomes available over the operational life of a system. The only study (Kamins, 1963) to address weapon system scheduled maintenance was a simulation conducted to determine optimal scheduled maintenance and operational test intervals. However, none of these studies addressed scheduling effectiveness as a function of workorder completions or management action.

More recent simulation studies of scheduling have been done in the area of aircraft and missile maintenance. Barnidge and Cioli (1978:251) incorporated aircraft maintenance into a system dynamics model of the wing-level

scheduling process for an aircraft wing. Ostrofsky (1980: 61) developed a Monte Carlo simulation of the maintenance system for a vertical launch MX Missile system. This model was a flexible, Fortran model designed to permit the analysis of a variety of maintenance strategies and scenarios on a macro level.

An important factor in the increased popularity of computer simulation has been the evolution of simulation languages from low-level machine languages (Fishman, 1978:7; Lehman, 1977:247). Pritsker has been one of the primary developers of simulation languages which are based on graphical network evaluation. He notes that there are several advantages to applying network analysis to scheduling and planning activities. These advantages are:

1. Networks are easily understood by all levels of personnel in the organizational hierarchy.
2. Networks can be used as a communication device as they provide a reference point for discussions.
3. Networks facilitate the identification of pertinent data collection.
4. Networks provide the capability to analyze the activity [Drezner and Pritsker, 1965:1].

One of the latest simulation languages to be developed by Pritsker is Q-GERT (Queuing - Graphical Evaluation and Review Technique). Q-GERT was adapted from a previous simulation language called GERT which generalized PERT concepts for computer analysis (Pritsker, 1979:vii). Q-GERT augments GERT with the addition of queuing and decisional capability (Pritsker, 1979:vii). In addition, Q-GERT allows for direct computer analysis of the network (Pritsker, 1979:vii).

Connolly and Johnson (1981:63) completed a Q-GERT simulation study which showed that the base level repair cycle for jet engines can be influenced by a change in the level of key maintenance resources. The BDM Corporation developed a Q-GERT simulation which models the "relevant operational aspects of the Air Launched Cruise Missile (ALCM) logistics support system [1980:I-1, I-3]," and includes scheduled and unscheduled maintenance activities.

In the area of general maintenance models, Kane (1981:23) developed a descriptive model based on the individual maintenance technician as the processor, with performance as the system output. The inputs in this model are all the other areas of logistics support which may or may not be optimized. Kane's main conclusion is that even with a perfect technician, suboptimal inputs will lead to suboptimal outputs.

This literature search revealed numerous research efforts in the areas of scheduling and maintenance efficiency and productivity. However, no studies were found which specifically addressed scheduling effectiveness as defined by the Strategic Air Command. In addition, no studies were found that specifically looked at the factors which determine an organization's ability to execute a daily maintenance schedule.

Scope of Research

The simulation model for this study will be developed for one Minuteman Missile maintenance organization, and will be based on data obtained from that organization. The results should be similar to what they would be for other Minuteman Missile maintenance organizations. However, any attempts to generalize the model to other organizations should take into account the inter-wing differences caused by differences in personnel, equipment, geography, and weapon systems.

Research Questions

1. Can the probability distributions of the factors which result in incomplete scheduled workorders be identified?
2. Can the execution of the daily maintenance schedule be accurately represented by a dynamic simulation model which uses the number of scheduled workorders and random schedule deviations as inputs?
3. Could such a model (as described in question 2 above) be used to identify those areas in which management attention could produce the greatest increase in scheduling effectiveness?

Research Objectives

1. Identify the controllable factors or variables which most frequently result in incomplete scheduled workorders.
2. Examine those factors to determine whether they conform to any known probability distributions.
3. Develop a simulation model which uses the distribution of scheduled workorders and the distributions of the reasons for incomplete scheduled workorders as inputs. This model would be used to simulate the effect of these distributions on the scheduling effectiveness rate.
4. Perform a sensitivity analysis by varying the parameters of the input distributions. This would simulate the effect of management action intended to improve scheduling effectiveness.
5. Identify the area(s) in which management attention could result in the greatest improvement in scheduling effectiveness.

CHAPTER 3

METHODOLOGY

Introduction

This chapter describes the development of a computer simulation model of the Minuteman Missile Maintenance Schedule Execution System (henceforth referred to as the Schedule Execution System or SES). This chapter will consider the first eight steps in the simulation process outlined by Shannon. These eleven steps which comprise the simulation process are:

1. System Definition - Determining the boundaries, restrictions and measures of effectiveness to be used in defining the system to be studied.
2. Model Formulation - Reduction or abstraction of the real system to a logic flow diagram.
3. Data Preparation - Identification of the data needed by the model, and their reduction to an appropriate form.
4. Model Translation - Description of the model in a language acceptable to the computer to be used.
5. Validation - Increasing to an acceptable level the confidence that an inference drawn from the model about the real system will be correct.
6. Strategic Planning - Design of an experiment that will yield the desired information.
7. Tactical Planning - Determination of how each of the test runs specified in the experimental design is to be executed.
8. Experimentation - Execution of the simulation to generate the desired data and to perform sensitivity analysis.
9. Interpretation - Drawing inferences from the data generated by the simulation.
10. Implementation - Putting the model and/or results to use.

11. Documentation - Recording the project activities and results as well as documenting the model and its use [Shannon, 1975:23].

Step 9 will be the general topic of Chapters 4 and 5. The last two steps, 10 and 11, generally describe the overall content of the remainder of this study. Therefore, they will not be explicitly addressed in any one chapter.

The first step in the simulation process was accomplished in Chapter 2. Therefore, this chapter will begin with step 2--model formulation.

Model Formulation

A logic flow diagram which is representative of the Schedule Execution System is shown in Figure 3-1. Although simplistic, the flow diagram describes the key elements of the SES, while it leaves out trivial and inconsequential details which add little or nothing to an understanding of the basic input to output transformation. This is as it should be, for as Shannon states: "the model must include only those aspects of the system relevant to the study objectives [1975:27]."

The model presented is based on the following assumptions:

1. The scheduled workorder input consists of workload requirements (jobs which need to be performed) and the resources required to complete those requirements.
2. Higher rates of scheduling effectiveness are desirable.

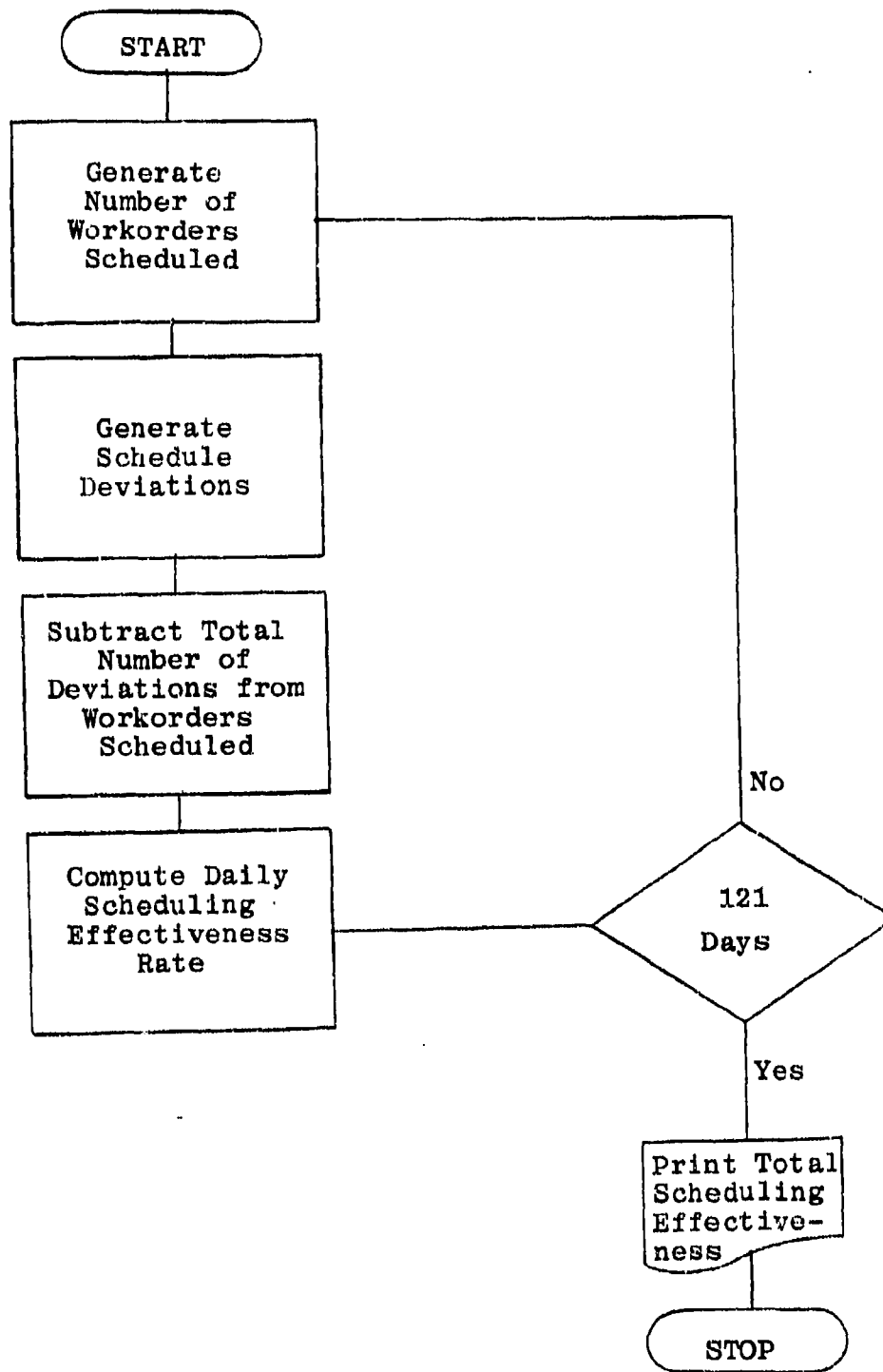


Figure 3-1. Flow Diagram of the Simulation

3. Any deviation generated will prevent the completion of a scheduled workorder on a one-to-one basis.

4. The number of vehicle and equipment and personnel caused deviations can be reduced, at least partially, through management actions. Hence, these deviations are at least semi-controllable.

5. Management resources which can be applied to reduce the number of controllable deviations are limited.

Data Preparation

The next aspect of the system simulation process is the Gathering and Processing of Data. For this study, the data consists of a six month sample (180 individual days) which includes the following:

1. The number of workorders scheduled per day.
2. A computer generated listing of all deviations which resulted in incomplete scheduled workorders. The cause (e.g., higher priority maintenance, personnel error, lack of parts, etc.) was provided for each deviation.
3. The number of scheduled workorders completed each day.

This data was examined and all weekends and holidays were deleted from the sample. This was done so that the extremely low number of workorders scheduled at these times would not distort the frequency distributions of the "normal" workdays. This reduced the sample size to 121 days.

The data was next stored in computer data files to facilitate the appropriate goodness-of-fit tests for determining the respective probability distributions of the data categories. These categories initially consisted of the following data, listed by day:

1. The number of workorders scheduled (SCH).
2. The number of workorders completed (COMP).
3. The number of deviations due to personnel error (PERS).
4. The number of deviations caused by vehicle and equipment (VE) problems. (These deviations were later added to the uncontrollable deviation category because missile maintenance units generally consider these deviations to be uncontrollable.)
5. The number of deviations caused by uncontrollable factors (UNC).

At this point, research question number one was examined: do the frequency distributions of the main factors (deviation categories) which result in incomplete scheduled workorders conform to underlying theoretical probability distributions?

The number of occurrences within each deviation category is a discrete random variable. This type of variable is one which can be counted, and corresponds to integer (whole number) values (McClave and Benson, 1979:116). A discrete random variable can be contrasted with a continuous

random variable in that the latter can take on an infinite number of values. That is, a continuous random variable can be represented by either integer or real numbers (McClave and Benson, 1979:117). The scheduling effectiveness rate is an example of a continuous random variable. It can be expressed as either an integer or real number, and can assume an indeterminate number of values.

Of the five data categories listed, categories three through five are of primary concern in regard to the research question asked above. As this data is discrete, if the respective probability distributions can be identified, they should conform to discrete theoretical probability distributions. In attempting to identify these underlying theoretical distributions, a procedure advocated by Shannon was used (1975:72-74). First, a computer generated chart (histogram) of the frequency distribution was observed for each category. These histograms were then compared to drawings of several typical distributions to determine potential candidates. In addition, the characteristics of these theoretical distributions were examined to narrow the range of potential candidates.

First to be examined was the Personnel Error (PERS) deviation category. The histogram for this variable displayed characteristics similar to the exponential distribution; however, the exponential distribution is continuous, not discrete. The most likely candidate for the PERS

variable appeared to be the Poisson distribution. McClave and Benson list the characteristics of a Poisson random variable as:

1. The experiment consists of counting the number of times a particular event occurs during a given unit of time
2. The probability that an event occurs in a given unit of time . . . is the same for all units.
3. The number of events that occur in one unit of time . . . is independent of the number that occur in other units.
4. The mean (or expected) number of events in each unit will be denoted by the Greek letter lambda . . . [1979:138].

The characteristics of the PERS variable closely matched those of a Poisson random variable.

The next step was to perform an appropriate goodness-of-fit test to see whether the PERS distribution was significantly different from a discrete, theoretical Poisson distribution. Two goodness-of-fit tests were considered for this task: the Chi-square and the Kolmogorov-Smirnov (K-S). A computer program called the Statistical Package for the Social Sciences (SPSS) provides the capability for using the K-S test for a Poisson distribution (Hull and Nie, 1981: 224). This capability is provided despite the fact that one of the assumptions of the K-S test is a continuous distribution. This capability, in addition to the relative simplicity of the K-S test led to its election for goodness-of-fit testing. The statistical hypothesis used to determine goodness-of-fit was:

H_0 : The PERS variable is Poisson distributed with lambda as specified.

H_a : The PERS variable is not Poisson distributed with lambda as specified.

The results of the test failed to support the null hypothesis and can be found in Table 3-1.

Three additional discrete probability distributions were next considered. These were the binomial, the geometric and the hypergeometric. The first two of the above distributions can appear in an exponential-like distributional form, while the third appears somewhat Poisson.

The next step taken was to determine whether the characteristics of the PERS variable conformed to the characteristics of any of these discrete random variables. The first of the above distributions to be considered was the binomial. McClave and Benson list the characteristics of a binomial random variable as:

1. The experiment consists of n [a given number] identical trials.
2. There are only two possible outcomes on each trial . . . denote one outcome by S (for Success) and the other by F (for Failure).
3. The probability of S remains the same from trial to trial
4. The trials are independent.
5. The binomial random variable x is the number of S 's in n trials [1979:128].

Of the above characteristics, it was relatively clear that characteristic number one could not realistically be applied to the PERS variable. The number of workorders scheduled per day could be equated with experimental trials,

Table 3-1
Statistical Hypothesis 1

H_0 : The PERS variable is Poisson distributed
with $\lambda = 2.116$

H_a : The PERS variable is not Poisson dis-
tributed with $\lambda = 2.116$

alpha level = .1

(Note: use Lilliefors Tables)

$$T = .1605 \qquad W_{.9} = \frac{.805}{\sqrt{121}} = .0732$$

Reject H_0 if $T > W_{.9}$

$T > W_{.9}$. Therefore, reject H_0 .

and these were clearly not identical. In addition, the possibility of more than two outcomes was extremely likely. That is, partial success (denoted by the scheduling effectiveness rate) added a third condition to the set of possible outcomes. In sum, it appeared that the binomial distribution could be eliminated from consideration.

The geometric distribution was next considered. This type of random variable has characteristics which closely resemble the binomial (McClave and Benson, 1979:146). One of these is that "each trial results in only one of two outcomes." This has already been shown to be an invalid characteristic in regard to the PERS variable. Therefore, this distribution was also rejected.

The final discrete random variable considered was the hypergeometric. McClave and Benson list its characteristics as:

1. The experiment consists of randomly drawing n elements without replacement from a set of N elements, r of which are S's (for Success) and $(n - r)$ of which are F's (for Failure).
2. The hypergeometric random variable x is the number of S's in the draw of n elements [1979:142].

Two conditions caused this distribution to be eliminated from consideration. First, like the two preceding distributions, "each draw or trial results in one of two outcomes [McClave and Benson, 1979:142]." Second, in a hypergeometric experiment, the results of sequential trials are dependent, rather than independent (McClave and Benson, 1979:142). In the real world system addressed by this study,

a given day's schedule (and any deviations which occur) is generally independent of a preceding day's schedule. There are some exceptions (such as the rescheduling of incomplete, high priority workorders), but in general, independence is more frequently a fact than is dependence.

Although an appropriate discrete theoretical distribution could not be identified for the PERS variable, it was determined that it could be reasonably approximated by an exponential distribution. This was accomplished by comparing a computer generated exponential variable with the historical (PERS) data. If the data sets did not differ significantly, it could then be inferred that the PERS variable roughly approximated an exponential distribution. The significance of this is that the PERS variable could be generated by the computer's internal exponential generator, thus facilitating its experimental manipulation.

The computer program used to generate the exponential variates that were used for test purposes is shown in Appendix A. An examination of this program will show that it converts real values drawn from a continuous distribution into integer values which represent a discrete distribution. This is accomplished by the process of truncation. An example of truncation is the conversion of the real value 3.124 to the integer value 3. This procedure is useful in that it yields a distribution which closely represents the

"real world" data, despite the fact that the latter is not continuous.

A Chi-square goodness-of-fit test was used in this instance (the computer K-S program lacked the capability to test exponential distributions) to test the hypothesis:

H_0 : The computer generated, modified exponential distribution did not differ significantly from the PERS distribution.

H_a : The distributions are significantly different.

The results of the Chi-square test support the null hypothesis and can be found in Table 3-2.

The next deviation category examined was UNC. This category also included VE data (for reasons previously explained). The histogram for the UNC variable also appeared to be Poisson distributed, and a K-S test was used to evaluate the following hypothesis:

H_0 : The UNC variable is Poisson distributed with lambda as specified.

H_a : The UNC variable is not Poisson distributed with lambda as specified.

The results of the test failed to support the null hypothesis and can be found in Table 3-3.

In addition to the Poisson, the other three discrete distributions were considered as potential candidates for the UNC distribution. However, these were also eliminated

Table 3-2
Statistical Hypothesis 2

H_0 : The computer generated, modified exponential distribution did not differ significantly from the distribution of the PERS Variable

H_a : The above distributions are significantly different

alpha level = .1

$$\chi^2 = 9.571$$

$$W_{.9} = 10.64 \text{ with 6 degrees of freedom (df)}$$

$$(df = 7 \text{ classes} - 1 = 6)$$

Reject H_0 if $\chi^2 > W_{.9}$ with 6df

$W_{.9} > \chi^2$. Therefore, do not reject H_0 .

Table 3-3
Statistical Hypothesis 3

H_0 : The UNC variable is Poisson distributed
with $\lambda = 4.124$

H_a : The UNC variable is not Poisson distributed with λ as specified

alpha level = .1

(Note: use Lilliefors Tables)

$$T = .2671 \qquad W_{.9} = \frac{.805}{\sqrt{121}} = .0732$$

Reject H_0 if $T > W_{.9}$

$T > W_{.9}$. Therefore, reject H_0 .

from consideration for the same reasons given in the prior section on the PERS variable.

Although the UNC variable did not appear to belong to any of the above discrete distributions, it was determined that the UNC distribution could be closely approximated by a modified exponential distribution similar to that generated for the PERS variable. A Chi-square goodness-of-fit test was used to compare the computer generated data distribution with the distribution of the historical UNC variable. The hypothesis test was:

H_0 : The computer generated, modified exponential distribution does not differ significantly from the UNC distribution.

H_a : The distributions are significantly different.

The results of the Chi-square test support the null hypothesis and can be found in Table 3-4.

The computer program used to generate the modified exponential distribution is shown in Appendix B. An examination of this program will show that the continuous to discrete conversion process is slightly different from that used for the PERS variable. the UNC generator adds a value of .5 to each computer generated value and then truncates the result, whereas the latter merely uses truncation. Here again, the procedure is useful in that it approximates the actual historical data.

Table 3-4
Statistical Hypothesis 4

H_0 : The computer generated, modified exponential distribution does not differ significantly from the distribution of the PERS variable

H_a : The above distributions are significantly different

alpha level = .1

$$\chi^2 = 10.258$$

$$W_{.9} = 14.68 \text{ with 9 degrees of freedom (df)}$$

$$(df = 10 \text{ classes} - 1 = 9)$$

Reject H_0 if $\chi^2 > W_{.9}$ with 9df

$W_{.9} > \chi^2$. Therefore, do not reject H_0 .

In order to model the Schedule Execution System, it was also necessary to attempt to identify the theoretical distribution of the number of workorders scheduled (SCH). An examination of a histogram of this data showed that the frequency distribution appeared approximately normally distributed. Again, however, the SCH variable is discrete while the normal distribution is continuous.

The SCH variable was first compared with the four discrete distributions examined earlier. The binomial, hypergeometric and geometric distributions were eliminated from consideration for the same reasons presented in the discussion of the PERS variable.

The Poisson distribution seemed a likely candidate for the SCH variable, and a K-S goodness-of-fit test was used to evaluate the following hypothesis:

H_0 : The SCH variable is Poisson distributed with lambda as specified.

H_a : The SCH variable is other than Poisson distributed with lambda as specified.

The results of the test failed to support the null hypothesis and can be found in Table 3-5.

A K-S goodness-of-fit test was then performed to test the hypothesis:

H_0 : The distribution of the SCH variable does not differ significantly from a normal distribution with a mean and standard deviation as specified.

Table 3-5
Statistical Hypothesis 5

H_0 : The SCH variable is Poisson distributed
with $\lambda = 41.537$

H_a : The SCH variable is not Poisson distributed with λ as specified

alpha level = .1

(Note: use Lilliefors Tables)

$$T = .2510 \qquad W_{.9} = \frac{.805}{\sqrt{121}} = .0732$$

Reject H_0 if $T > W_{.9}$

$T > W_{.9}$. Therefore, reject H_0 .

H_a : The distribution of the SCH variable differs significantly from a normal distribution with mean and standard deviation as specified.

The results of the test strongly supported H_0 (.1 level) and can be found in Table 3-6.

Model Translation

The next step in the system simulation process which was accomplished was Model Translation. The basic mathematical equations which capture the essence of the Schedule Execution System transformation process are:

$$1. \frac{\text{Scheduled Workorders Completed}}{\text{Workorders Scheduled}} = \frac{\text{Personnel Caused Deviation}}{\text{Uncontrollable Deviations}}$$

$$2. \text{Scheduling Effectiveness} = \frac{\text{Scheduled Workorders Completed}}{\text{Workorders Scheduled}} \times 100$$

These equations can be used for any unit of time (e.g., daily, monthly, etc.). In order for the SES system to be simulated by a computer model, the process illustrated by the above equations had to be converted into a computer language.

This study uses Q-GERT as the simulation language, with Fortran inserts as supplements to the Q-GERT model. The entire simulation could have been written in Fortran, but would have been much more cumbersome to use than the Fortran based Q-GERT language. The Q-GERT model is much more compact than an equivalent Fortran model would have

Table 3-6
Statistical Hypothesis 6

H_0 : The SCH variable is normally distributed with mean = 41.537 and standard deviation = 15.909

H_a : The SCH variable is not normally distributed with mean and standard deviation as specified

alpha level = .1

(Note: use Lilliefors Tables)

$$T = .0576 \qquad W_{.9} = \frac{.805}{\sqrt{121}} = .0732$$

Reject H_0 if $T > W_{.9}$

$W_{.9} > T$. Therefore, do not reject H_0 .

been, and allows more simple manipulation for experimentation purposes.

The Q-GERT network model used in this study is illustrated in Figure 3-2. The Q-GERT program and its subprograms (user-functions) are presented in Appendix C. The model performs the basic processes illustrated in Figure 3-1, and simulates 121 days of activity. The basic operation of the model is as follows: First, each day's scheduled workorders are generated. Second, deviations which result in incomplete scheduled workorders are generated and the total number of deviations of each type are subtracted from the number of scheduled workorders. Finally, the scheduling effectiveness rate for each day is computed, and the next day's activities are initiated. After 121 days of activity have been generated, the model computes final statistics, prints them out and then stops.

At this point a brief description of the Q-GERT nodes and notation used in the model is in order.¹ The segmented, cylindrical shaped figures in Figure 3-2 are called Regular Nodes, and are numbered left to right as one (1) through four (4). Model activity begins at node 1 (which is called a Start Node) and ends at circularly shaped, End Node number five (5). The lines connecting the nodes are called Branches.

¹All symbols, notation and functional structure used in this section are drawn from Pritsker (1978:Ch.3,Ch.6).

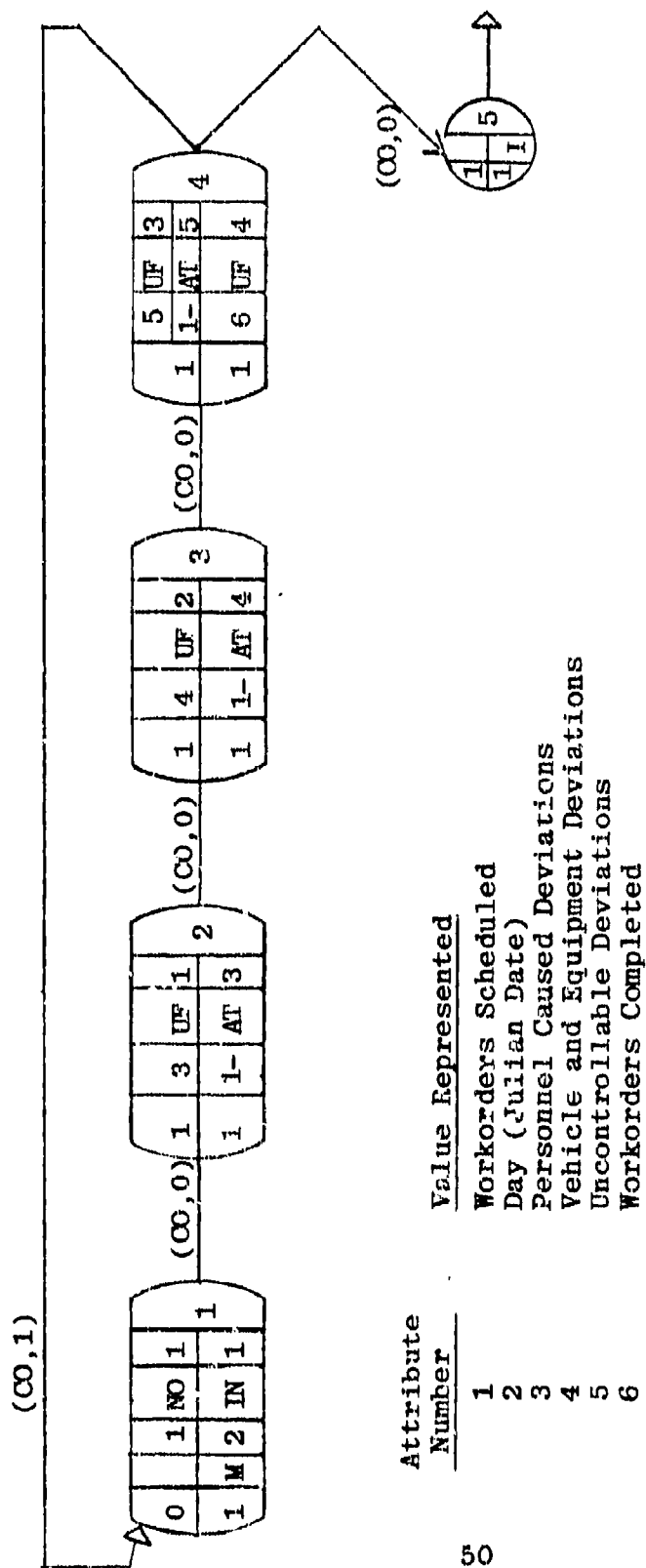


Figure 3-2. Q-GERT Network of Model

Each day's activity begins at Node 1, where a given day's scheduled workorders are generated. This simulates the completed daily maintenance schedule. It is assumed that each day's schedule represents not only workorders but all the resources required to fully execute that schedule. The daily schedule (as generated in the model) is known in Q-GERT terminology as a transaction: an entity that will be processed through the entire network.

A given transaction can have a number of attributes (characteristics) associated with it. Schedule Execution System transactions are assigned six (6) attributes as shown in Figure 3-2. Hence, any given daily maintenance schedule has the characteristics of: (1) a number of scheduled workorders; (2) a Julian date (sequential number beginning with one for January 1st); (3) deviations which caused incomplete workorders (labeled 3, 4, and 5); and (4) a resultant number of workorder completions (labeled 6). The SES model processes the transactions through nodes 2, 3, and 4 where deviations are generated and the number of these deviations is subtracted from the daily schedule. As transactions leave node 4, the next day's activity is generated. Transactions are processed through End Node 5 where they then vanish from the system. After 121 transactions are generated, the model stops.

While the Q-GERT network illustrated in Figure 3-2 is the essence of the SES model, Fortran subprograms called

user functions perform many of the computations necessary for the model to operate. These user functions primarily perform mathematical computations and are "called" as needed by the Q-GERT Program.

Validation

The next phase in the simulation process involves model validation. Shannon states that "there is no such thing as the 'test' for validity [1975:28]." Yet, validation can be accomplished even without such a test. He describes one view of validation in which it consists of three sub-activities: verification, validation, and problem analysis. Verification determines whether "the model behaves as the experimenter intends." Validation compares the degree to which a model and the actual system it represents behave the same. Problem analysis concerns "analysis and interpretation of the data generated by the experiment [1975:210]."

In terms of the overall simulation process, it appears that the problem analysis sub-activity is more properly a component of the interpretation phase than of the validation phase. Therefore, only the first two sub-activities will be discussed in this section, with problem analysis being reserved for discussion in Chapters 4 and 5.

Verification is easily accomplished by generating a trace of computer activity and examining that trace for the occurrence of desired simulation activity. In this instance,

the model should generate a finite number of scheduled workorders and deviations for each of the 121 simulated days of activity. It should then perform the necessary mathematical computations and print out the desired data and statistics. An examination of the computer generated trace showed that these intended activities were in fact being accomplished.

However, at this point in the validation process, it was apparent that something was wrong with the model. Scheduling effectiveness rates generated by the simulation displayed much greater variability than those encountered in the actual system.

An examination of the historical data showed that the scheduling effectiveness rate remained relatively constant over the entire range of the number of workorders scheduled. If this was assumed to be true, then the actual number of total deviations had to increase as a function of the number of workorders scheduled.

Up to this point, the model was using modified exponential variates (previously discussed) to simulate UNC and PERS deviations. However, a basic problem in using this method of generating deviations was the fact that the relationships between the number of deviations which occurred, and the number of workorders scheduled was not being captured by the model. Furthermore, by using only one distribution to generate deviations over the entire range of workorders scheduled, it was possible for the model to permit

the number of deviations to exceed the number of scheduled workorders, an unrealistic situation. What was required was some method of generating deviations which captured the relationships between this variable and the number of workorders scheduled.

The first method examined involved an attempt to identify probability distributions within smaller ranges of workorders scheduled for each deviation category. However, obtaining the desired accuracy in the relationship between deviations and workorders scheduled would have required extensive goodness-of-fit testing, in some cases with as few as fifteen to twenty historical data points.

Q-GERT (Pritsker, 1979:251-252) permits a modeler to generate variates which are samples from an actual (real world) "probability mass function." The function used to accomplish this is called "DPROB". This function looked promising from the standpoint of capturing the relationship between workorders scheduled and the number of deviations generated.

In arriving at the division of the data into categories, a computer generated plot (scattergram) of scheduling effectiveness (vertical scale) as a function of the number of workorders scheduled (horizontal scale) was examined. The number of data points was greatest within one standard deviation about the mean of the number of workorders scheduled, with lesser numbers of points outside this range.

After examining the scattergram, it appeared that any arbitrary division of the data (along the horizontal axis) could be used. In an attempt to more accurately capture the relationship between deviations and the number of workorders scheduled, while at the same time keeping the number of categories manageable (for experimental purposes) it appeared that four categories would be a satisfactory number of sub-ranges within the range of workorders scheduled.² Different probability functions were then used to generate deviations, with the probability function based on the number of workorders scheduled. Thus, each deviation category (PERS, VE, or UNC) had four possible probability distributions, with this function dependent upon the number of workorders scheduled for that particular day.

After incorporating the above change into the simulation, the variability in the simulated scheduling effectiveness became a much closer approximation of typical historical scheduling effectiveness rates. It was therefore decided to permanently incorporate DPROB generated deviations in lieu of the modified exponential variates previously used. At this point, the model was considered to be verified.

The second sub-activity (validation) can be accomplished by a test which compares the output of the model with

²In conducting the experiment, it was decided to break out the number of VE deviations from the UNC category in order to determine the effect of the former on the scheduling effectiveness rate.

that derived from the actual system. Various tests are available for this purpose, but their use depends on the assumptions made regarding the data to be compared. Two commonly used tests are means tests, and goodness-of-fit tests (Shannon, 1975:219). Another potentially applicable test which is similar to a test of means is a test of proportions (McClave and Benson, 1979:278).

The data which is to be compared are the respective daily scheduling effectiveness rates from the simulation model and the actual, real world system. The first category of tests considered for the comparison were tests-of-means. Shannon (1975:220) presents a table which can be used to select the most appropriate test depending on the characteristics of the data being compared.

The underlying population variance and population mean for the daily scheduling effectiveness rate was unknown. In order to narrow the range of applicable tests, it was necessary to determine whether the variances of the two sample data sets compared were significantly different. An F-test is generally used to determine whether two sample variances are equal. However, the F-test assumes that the "sampled populations are normally distributed [McClave and Benson, 1979:263]."

In order to determine whether the respective daily scheduling effectiveness variables were normally distributed, K-S goodness-of-fit tests (using the Lilliefors Tables) were

used to compare these with a normal distribution. The hypothesis tested for each was:

- H_0 : The scheduling effectiveness variable is normally distributed with mean and standard deviation as specified.
- H_a : The scheduling effectiveness variable is not normally distributed with mean and standard deviation as specified.

The results of the first test (historical scheduling effectiveness) resulted in rather weak (.01 level of significance) support for the null hypothesis (see Table 3-7). The results of the second test (model generated scheduling effectiveness) failed to support the null hypothesis (see Table 3-8). Based on these results, and the fact that the remaining means tests depended in part on the same normality assumption as the F-test, the test-of-means category was eliminated from consideration.

The test-of-proportions was next considered. However, this test is based on the assumption that the proportions being compared are the result of binomial experiments (McClave and Benson, 1979:235). In this case, the binomial assumption of identical trials could not be adequately justified, and, therefore, this test was also rejected.

The K-S two sample test for goodness-of-fit was next considered. This test compares "the empirical relative cumulative frequency functions obtained from two samples [Wolf, 1974:182]." According to

Table 3-7
Statistical Hypothesis 7

H_0 : Daily scheduling effectiveness is normally distributed with mean = 85.392 and standard deviation = 9.512

H_a : Daily scheduling effectiveness is not normally distributed with mean and standard deviation as specified above

alpha level = .01

(Note: use Lilliefors Tables)

$$T = .0824 \qquad W_{.99} = \frac{1.031}{\sqrt{121}} = .0937$$

Reject H_0 if $T > W_{.99}$

$W_{.99} > T$. Therefore, do not reject H_0 .

Table 3-8
Statistical Hypothesis 8

H_0 : Computer generated daily scheduling effectiveness is normally distributed with mean = 83.253 and standard deviation = 10.6

H_a : Computer generated daily scheduling effectiveness is not normally distributed with mean and standard deviation specified above.

alpha level = .01

(Note: use Lilliefors Tables)

$$T = .0781 \qquad W_{.99} = \frac{1.031}{\sqrt{121}} = .0937$$

Reject H_0 if $T > W_{.99}$

$T > W_{.99}$. Therefore, reject H_0 .

Hull and Nie, "this is sensitive to any type of difference in the two distributions . . . [1981:232]." In addition, the test situation under consideration satisfied all assumptions necessary for the K-S two sample test. All things considered, this test appeared appropriate and was selected.

The test was conducted in order to evaluate the following hypothesis:

H_0 : The cumulative distribution functions of both samples are equal.

H_a : The cumulative distribution functions of both samples are not equal.

The results of the test provided strong support (.1 level of significance) for the null hypothesis, and are presented in Table 3-9.

Strategic Planning

The next step in the simulation process to be discussed is strategic planning. This term simply refers to the design of an experiment which will yield insight into the problem under study (Shannon, 1975:30-31). Shannon (1975:144-149) states that this phase of the process is important because it determines to a significant degree both the effectiveness and the efficiency of the simulation. According to Shannon (1975:150-151), the reason for conducting an experiment is to determine what effect a given change in one or more factors (independent variables) has on some response variable (dependent variable). The design process

Table 3-9
Statistical Hypothesis 9

H_0 : The cumulative distribution functions
of both samples are equal

H_a : The cumulative distribution functions
of both samples are not equal

alpha level = .1 (Two Sided Test)³

$T = .0909$

$W_{.9} = .1573$

Reject H_0 if $T > W_{.9}$

$W_{.9} > T$. Therefore, do not reject H_0 .

³Critical values are from Conover (1971:399).

used in this study will follow the three step process presented by Shannon:

1. Design of the structural model
2. Design of the functional model
3. Design of the experimental model [1975:151].

In developing the structural model, it is necessary to determine which factors (independent variables) will be used, and how many levels of each of these factors should be considered. However, a condition precedent to this is the identification of the response variable of interest (Shannon, 1975:153). For reasons already presented, the response variable of interest in this study is the scheduling effectiveness rate. Likewise, the independent variables of concern are those factors which influence the scheduling effectiveness rate by causing incomplete scheduled work-orders.

One aspect of structural model design mentioned above is the determination of the number of levels of each factor to be considered. For purposes of this study, it was determined that three levels of each of two factors (VE and PERS) would be used. These levels were, for both factors: (1) a 10 percent decrease in the mean number of deviations; (2) a condition of no change; (3) a 10 percent increase in the mean number of deviations. These levels were selected for ease of manipulation, experimental efficiency, and because they appeared to be realistic alternatives.

In designing the functional model, the primary consideration is to determine the fraction of total cells (there would be a total of nine cells in the experiment: 3 levels x 3 levels) that "will actually contain a response measurement . . . [Shannon, 1975:155]." It was determined that all cells would be used as response variable measurements so that the functional model would be "complete . . . the ideal situation . . . [Shannon, 1975:155]."

The design of the experimental model for an experiment containing two or more factors boils down to a choice between a "full factorial design" or a "fractional factorial design [Shannon, 1975:163-169]." The primary difference between the two involves the number of samples (computer runs) required for each. The full factorial design is preferable from a statistical standpoint, but also requires more samples (Shannon, 1975:166). Shannon states that the full factorial design is preferable if "the number of factors is . . . less than 5 [Shannon, 1975:167]." For this reason, the full factorial design was selected.

Tactical Planning

The next area of focus concerns the seventh step in Shannon's simulation process: tactical planning. Two problems need to be resolved in this phase (Shannon, 1975:31). The first of these deals with the "starting conditions" of the model. The second concerns the requirement for minimizing

the variance of the dependent variable while simultaneously minimizing the sample size.

Due to the nature of this simulation, starting conditions are not a significant problem. In some studies, a model must run until a steady state condition is achieved that closely resembles the normal operating conditions of the real system. For example, it may be necessary to simulate the passage of a given amount of time before a model is considered to be operating under realistic conditions. However, the model used in this study does not require any time accumulation as it is only intended to simulate already existing steady state conditions.

While the first problem is not significant in the context of this study, the second most certainly is. That is, how many samples (generated random variates) must one obtain to achieve the level of accuracy desired? Greater accuracy can be achieved merely by increasing the number of samples used in an experiment. However, this accuracy is obtained at the cost of increased computer time. Additionally, this accuracy is "inversely proportional to the square root of the number of observations," and hence is rather inefficiently obtained (Shannon, 1975:181). Shannon (1975:190) presents a table which can be used to determine the sample size needed for a given level of accuracy in estimating the mean of a dependent variable. The table is based in part on Tchebycheff's Theorem and permits one to estimate

sample size even though the response variable may not be normally distributed (which appears to be the case).

For purposes of this study, it was felt that an accuracy level of plus or minus one fourth of a standard deviation (roughly 2.4 percentage points of the scheduling effectiveness rate) about the true mean scheduling effectiveness rate would be sufficiently accurate. For this level of accuracy, and a .05 level of significance, the referenced table indicated the required sample size to be 320. In order to match this number with the structure of the model, a sample size of 363 (121 x 3 runs) was used.

Experimentation

The final step in the simulation process to be discussed in this chapter is experimentation. That is, the systematic variation of the input variables in order to determine the effect on the response variable (Shannon, 1975:32). As stated earlier, the input variables were varied by approximately plus or minus ten percent. This was accomplished by substituting different cumulative probability values into the user function portion of the model. The model was then run three times for each possible combination of the two factors.

A factorial design experiment was chosen to determine the effect of the input variables PERS and VE on scheduling effectiveness. Shannon notes that, "an experiment

on one factor would seldom be considered as adequately replicated unless it had about eight samples at each level [1975:164]."

A factorial experimental design is one in which all levels of a given factor are combined with all levels of every other factor in the experiment (Shannon, 1975:164). Thus, a two factor experiment with three levels for each factor would yield a nine cell experiment. The advantage of the factorial design is that the number of replications per cell can be reduced while a sufficient number of replications is retained for each level (row or column) of each factor (see Figure 3-3). In this case, only three replications per cell are required to yield nine replications per level.

| | | PERS | | |
|----|-----|------|----|-----|
| | | -10 | NC | +10 |
| VE | -10 | x | x | x |
| | | x | x | x |
| | | x | x | x |
| | NC | x | x | x |
| | | x | x | x |
| | | x | x | x |
| | +10 | x | x | x |
| | | x | x | x |
| | | x | x | x |

Figure 3-3. Two-Factor, Three Level, Factorial Experimental Design

Analysis of variance (ANOVA) enables one to test whether there is a significant difference "between more than two sample means [Levin, 1978:300-301]." If these sample means are each a measure of the response variable of an individual experiment, then a significant difference between the means indicates that the experimental manipulation of an independent variable has had a statistically significant effect (Levin, 1978:302). In this situation, ANOVA will be used to determine if at least one of the factors (PERS or VE) has a significant impact on scheduling effectiveness.

This chapter has described the development of the Schedule Execution System model. It traced the first eight steps in the system simulation process advocated by Shannon which culminate in the experimental manipulation of the model.

The next step to be accomplished in the process is interpretation. Chapter 4 will present the statistical interpretation of the foregoing experimentation, and Chapter 5 will then discuss the implications of the results presented in Chapter 4.

CHAPTER 4

RESULTS

This chapter summarizes the results of the simulation experiment discussed in the previous chapter. In terms of the system simulation framework presented by Shannon (1975: 23), this is one aspect of the interpretation step. A second aspect of this step is a discussion of the inferences drawn from the experimental results. However, this latter aspect, unlike the former, is more properly part of the Conclusions and Recommendations chapter, and will, therefore, be discussed in Chapter 5.

A two factor factorial experiment was used to test the impact of a plus or minus ten percent change in the level of PERS and VE deviations on the scheduling effectiveness rate. Experimentation with two factors at three levels results in a nine cell experimental design. In order to meet the requirement (Shannon, 1975:164) that the experiment be replicated at least eight times at each level of each factor, three runs were accomplished for each cell. This procedure resulted in nine replications of the experiment for each level of each factor and a total of 27 replications for the experiment.

In the previous chapter, the cumulative probability distribution of the simulated daily scheduling effectiveness

rate was compared to the cumulative probability distribution of the historical daily scheduling effectiveness rate for purposes of model validation. At the operational level, however, the scheduling effectiveness rate is more of a long term measure and is seldom considered on a daily basis. In order to more accurately reflect the longer term aspect of this measure, the authors decided to use the total scheduling effectiveness rate for each run [i.e., total workorders completed divided by total workorders scheduled rather than the sum of the daily ratio (i.e., daily workorders completed divided by daily workorders scheduled) divided by 121 days]. It should be noted that the numbers involved are not changed and the only difference is in the method of calculating scheduling effectiveness.

The Statistical Package for the Social Sciences (SPSS) ANOVA program (Nie et al., 1975:421) was used to analyze the results of the experimentation. The results of this analysis are shown in Table 4-1. The table shows that the main effects portion of the model is significant to the .023 alpha level. This indicates that the mean of at least one of the experimental cells is significantly different from the means of the other cells.

Further examination of the ANOVA table shows that virtually all of the (controllable) variance explanation capability of the model comes from the PERS factor. The variance that is explained by the VE factor is

Table 4-1
ANOVA of Total Scheduling Effectiveness

| SOURCE OF VARIATION | SUM OF SQUARES | DF | MEAN SQUARE | F | SIGNIFICANCE OF F |
|---------------------|-------------------|----|----------------|-------|----------------------|
| MAIN EFFECTS | | | | | |
| PERS | 5.116 | 4 | 1.279 | 3.712 | 0.023 |
| VE | 4.961 | 2 | 2.480 | 7.198 | 0.005 |
| | 0.156 | 2 | 0.078 | 0.226 | 0.800 |
| 2-WAY INTERACTIONS | | | | | |
| PERS VE | 0.000 | 4 | 0.000 | 0.000 | 1.000 |
| | 0.000 | 4 | 0.000 | 0.000 | 1.000 |
| EXPLAINED | 5.116 | 8 | 0.640 | 1.856 | 0.131 |
| RESIDUAL | 6.203 | 18 | 0.345 | | |
| TOTAL | 11.319 | 26 | 0.435 | | |

almost nil (F value = .226) and interactions between the two factors contribute absolutely no information to the model (F value = 0.0).

The Multiple Classification Analysis program in SPSS (Nie et al., 1975:409-410) was used to further understand the results of this experiment. This analysis (Table 4-2) showed that the PERS factor explained 43.56 percent ($.66^2$) of the variability in the scheduling effectiveness rate, while the VE factor explained only 1.44 percent ($.12^2$) of the variability in the scheduling effectiveness rate. Together, these factors explained 45 percent of the variability in the scheduling effectiveness rate. This percentage is also represented by the ratio of sum of squares explained to sum of squares total in the ANOVA table.

Since only 45 percent of the variation in the scheduling effectiveness rate is explained by the two experimental factors, 55 percent of the variability is brought about by residual (nonexperimental) factors and by random error. In this case, the only residual factor is the level of uncontrollable deviations. These numbers imply that even if the controllable deviations (PERS and VE) were completely controlled or eliminated, variability in the scheduling effectiveness rate would only be reduced by 45 percent. Thus, the greatest cause of variability in the scheduling effectiveness rate lies in the residual or uncontrollable factors.

Table 4-2

Multiple Classification Analysis of
Total Scheduling Effectiveness

| Variable + Category | N | Unadjusted | | Adjusted for | |
|-------------------------|---|--------------------|------|--------------|-------|
| | | Dev'n ¹ | Eta | Dev'n | Beta |
| PERS ² | | | | | |
| -1 | 9 | 0.49 | | 0.49 | |
| 0 | 9 | 0.07 | | 0.07 | |
| 1 | 9 | -0.55 | | -0.55 | |
| | | | 0.66 | | 0.66 |
| VE | | | | | |
| -1 | 9 | 0.10 | | 0.10 | |
| 0 | 9 | -0.01 | | -0.01 | |
| 1 | 9 | -0.09 | | -0.09 | |
| | | | 0.12 | | 0.12 |
| MULTIPLE R ² | | | | | 0.452 |
| MULTIPLE R | | | | | 0.672 |

¹Dev'n "is simply the mean of each category expressed as a deviation from the grand mean. The ETA² for each factor indicates the proportion of variation in Y [scheduling effectiveness rate] explained by each factor [Nie et al., 1975:404]."

²-1 and 1 correspond, respectively, to a 10 percent decrease and a 10 percent increase in the mean number of deviations in each category (PERS and VE).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

A missile maintenance organization's production effort occurs in a highly dynamic and complex environment. Strategic deterrence depends to a great degree on the capability of missile maintenance organizations to be responsive to this environment. However, the organization must also be efficient in the accomplishment of maintenance. The daily maintenance schedule is essentially a tool which the organization uses in reaching a compromise between efficiency and responsiveness.

Scheduling effectiveness is one measure of the organization's efficiency in accomplishing its maintenance requirements. As stated earlier, scheduling effectiveness is the ratio of workorders completed to workorders scheduled. Thus, it follows that scheduling effectiveness is a function of the number of workorders scheduled and of the number of deviations to a schedule, with each deviation resulting in an incomplete workorder. There are many specific categories of deviations. However, they can generally be described as either controllable by management action or uncontrollable.

The focus of this study is on these determinant factors of scheduling effectiveness, and the possible effects

of management action to change the controllable factors and thus improve the scheduling effectiveness rate.

This research was accomplished by first analyzing historical data pertaining to the scheduling effectiveness rate at one missile wing. This data was then used to generate the inputs to a computer simulation as described in Chapter 3. Chapter 4 presented the results of the experimentation on the simulation model and showed the effect of simulated management action on controllable deviations and the scheduling effectiveness rate.

This chapter is divided into four sections: Limitations, Conclusions and Insights, Recommendations, and Summary. In terms of Shannon's simulation framework, the main theme of this chapter will be interpretation.

Limitations

As already mentioned, this study is based on data collected at a single missile wing during one particular time period. In addition, it must be remembered that inter-wing variations in missile type (e.g., Minuteman II, Minuteman III), configuration, geographical location, status of modifications, etc., can have a significant bearing on scheduling effectiveness. As a result of these factors, any attempt to generalize the results of this study should be done with a full awareness of the above limitations.

Conclusions and Insights

This section will address several conclusions drawn from the foregoing study of the Minuteman Missile Maintenance Schedule Execution System. Included here will be a discussion of the second aspect of the interpretation step first addressed in Chapter 4. Also included will be several insights gained by the researchers in the course of this study regarding scheduling effectiveness, schedule deviations, historical data, and future implications for missile maintenance managers. This will be accomplished using the research objectives stated in Chapter 2 as a discussion framework.

Research objective one.

Identify the controllable factors or variables which most frequently result in incomplete scheduled workorders.

This objective was attained quite early in the study. An examination of maintenance source data indicated that the most significant controllable factor was personnel error (PERS). This category actually consists of several types of personnel errors. It includes such things as ordering the wrong part, forgetting parts or necessary test equipment, allowing a job to be scheduled before all resources were available, etc.

The vehicle and equipment (VE) factor was initially thought to be critical, yet the data indicated that only a relatively small proportion of all deviations was attributable

to vehicle or equipment problems. In addition, VE type problems are generally considered to be uncontrollable rather than controllable, so the PERS factor is the only one remaining that is considered to be truly controllable.

From a manager's perspective, however, the frequency with which a controllable deviation occurs may not provide him with especially significant information within the context of all schedule deviations. For example, the model shows that a 10 percent reduction in the mean number of PERS deviations results in limited impact on the scheduling effectiveness rate. Similarly, a plus or minus ten percent change in the mean number of VE deviations (a somewhat controllable factor even though currently it is considered to be generally uncontrollable) causes little impact (both relatively and absolutely) on the scheduling effectiveness rate. Given that higher scheduling effectiveness rates are desirable, should a manager focus on these two areas only, because these factors alone are controllable?

The UNC category may contain other than truly uncontrollable factors. For example, a significant proportion of the deviations in this category are because of higher priority maintenance. In the context of a Strategic Missile Wing's mission, higher priority maintenance should generally take precedence over lower priority work, even if the latter is scheduled. Yet, does this mean that a higher priority

maintenance deviation should be considered to be inherently uncontrollable?

A higher priority maintenance caused deviation raises the issue of effectiveness versus efficiency. A wing (actually, the Job Control Branch) that cancels a scheduled job in deference to a higher priority requirement is acting, in general, effectively. This organization may also be acting efficiently, in that the schedule change is made in the most economical manner possible under the existing circumstances. However, if higher priority maintenance deviations could be found to occur with a given probabilistic frequency, could they not be planned for on a long term basis, thereby negating the requirement for many schedule deviations?¹

If this could be done (and this study makes no claim that it can), both the effectiveness and the efficiency of a wing's maintenance scheduling effort would increase. Any such increase in the scheduling effectiveness rate would, of course, have to be weighed against the marginal cost of obtaining it. This might prove very difficult to do, especially since a portion of the potential benefits (e.g., increased morale due to reduced job uncertainty) would be

¹This concept is different from the current Quick Reaction Maintenance concept in that Quick Reaction Maintenance teams are either surplus personnel resources on a given day or are only planned for on a short term or day to day basis.

intangible. Nevertheless, given that improved scheduling effectiveness can mean more efficient resource utilization, without sacrificing maintenance effectiveness, any avenue which increases the scheduling effectiveness rate should at least be considered.

Another aspect not captured by the incidence of controllable deviations in the maintenance source data is actual vehicle and equipment availability. At least some higher priority maintenance caused deviations occur because vehicles or equipment have to be withdrawn from a scheduled job or dispatch. In this case, additional vehicle or equipment resources (or, alternately, higher in-commission rates for available vehicles or equipment) could prevent at least some deviations. Hence, VE type problems probably have a much greater impact on the scheduling effectiveness rate than one might infer from an examination of the simulation results.

Research objective two.

Examine the factors identified by research objective one to determine whether they conform to known theoretical probability distributions.

This objective was accomplished to a degree. This requires further explanation. The frequency distributions of the PERS and UNC factors were compared with several theoretical distributions in attempting to identify a parent distribution for simulation purposes. Although it was shown statistically that the historical data distributions--as used in this

study--did not conform to any of the discrete distributions examined, the distributions could be closely approximated by modified, exponential distributions.

At this point, a word of caution is appropriate. In the course of this study, several discrete distributions were unsuccessfully screened as potential candidates for the factors of interest. Yet, it is possible that a discrete theoretical probability distribution exists that is representative of the historical data distributions. However, if such a distribution does exist, a disproportionate amount of time (in terms of benefits to be derived) may be necessary to locate it.

Another possibility is that the distribution of a larger number of data points (than was used in this study) may indeed conform to one of the more common discrete distributions. If this proves to be true, it could make future simulations of this type more easily accomplished.

Research objective three.

Develop a simulation model which uses the distribution of scheduled workorders and the distributions of the major deviation categories as inputs.

This research objective was accomplished. The model was verified and the output statistically validated. However, the level of data used in the model is too general to capture the hoped for interactions between factors. For example, the model uses the total number of workorders scheduled per day as one input, and the total number of each

type of deviation which results in incomplete scheduled workorders as the remaining input. This overall, aggregate data level fails to capture the impact that a single deviation might have on a dispatch which consists of x number of workorders. In other words, the single occurrence of a factor (e.g., one human error) may result in the cancellation of only one workorder, or it may result in the cancellation of 20 workorders. In the former, only one deviation has occurred; in the latter 20 have occurred. Both resulted from only one mistake. A more useful model might have been developed had the number of dispatch deviations been available for incorporation in the model in addition to workorder deviations.

Research objective four.

Perform a Sensitivity analysis by varying the parameters of the input distributions. This would simulate the effect of management action intended to improve scheduling effectiveness.

This objective was accomplished by the experimental simulation discussed in Chapters 3 and 4.

Research objective five.

Identify the areas in which management attention could result in the greatest improvement in scheduling effectiveness.

This objective was accomplished. However, in evaluating factors, it was implicitly assumed that approximately equal management attention is required for a given percentage change in the mean number of occurrences of both VE and PERS

deviations. This appears (to the authors) to be a reasonable assumption, but may not be valid in all situations.

Given that the above assumption is valid, the model shows that a 10 percent reduction in the mean number of PERS deviations will result in a much greater impact on the scheduling effectiveness rate than will a similar reduction applied to VE deviations (again assuming that VE deviations are at least partially controllable). Therefore, if the issues raised in research objective one regarding VE and higher priority maintenance deviations are considered to be invalid, then a manager could most favorably impact the scheduling effectiveness rate (other factors being equal) by concentrating on reducing the incidence of the PERS factor.

At this point, a discussion of some apparent implications of this study is appropriate. A good place to begin is with a reconsideration of the scheduling effectiveness measure. Two questions can be asked regarding the scheduling effectiveness rate. First, what does it actually measure? Second, what is its significance in the context of a missile wing's mission?

The scheduling effectiveness rate is, by definition, the scheduled workorder completion rate. But the term "scheduling effectiveness" is actually somewhat of a misnomer, for the workorder completion rate goes far beyond being just a measure of the effectiveness of the scheduling effort.

The post-scheduling meeting environment can be extremely unstable. As has already been noted, problems arise which threaten the full execution of a daily maintenance schedule, despite the best efforts of all concerned. (The number of deviations which occur are frequently only a fraction of the problems which confront the maintenance organization as it attempts to perform its mission.) When these problems occur, many players work together to overcome them, thereby ensuring that schedule integrity is maintained as much as possible. Therefore, far from merely being a measure of the effectiveness of the scheduling function, the scheduling effectiveness rate is a measure of the total maintenance organization's ability to plan and execute the maintenance schedule. The scheduling effectiveness rate can also be a partial measure of how well external agencies (e.g., Security Police or the Transportation Squadron) support the DCM complex.

With an understanding of what the scheduling effectiveness rate actually means, it then becomes necessary to examine the significance of this measure in terms of the wing's mission. To begin with, the scheduling effectiveness rate will probably always be of secondary importance relative to the wing's alert rate. This is quite logical because the alert rate is a "bottom line" measure in terms of the wing's mission. Effective strategic deterrence depends to a significant degree on the effectiveness of

strategic weapons, and the alert rate is one (but definitely not the only) measure of this effectiveness.

Scheduling effectiveness, however, may have little short term correlation (long term weapon system reliability is another matter) with the alert rate. The maintenance priority system places much emphasis on maintaining missiles in a high state of readiness. With this emphasis, one can easily see that, given the choice of either maintaining schedule integrity (and leaving missiles "off-alert") or maintaining a high alert rate, the latter will generally prevail. The significance of all this is that any policy which would enhance the scheduling effectiveness rate to the (significant) detriment of the alert rate would probably be short-lived.

Yet, does the subordinate position of the scheduling effectiveness rate mean that it is insignificant, and not worth improving? The answer to this is obvious: definitely not! Improved scheduling effectiveness rates mean higher efficiency. If this can be achieved without adversely impacting more important factors (e.g., effectiveness), then not only the individual maintenance organization, but higher level agencies will benefit as well. This is because resources saved in one area are resources which can be diverted elsewhere.

In studying the SES, it was hoped that a simulation model could be developed which would provide a DCM with a

"better" management/feedback device than the monthly analysis summaries currently in use. Although the particular form of the model developed in this study does not completely fulfill this expectation, it is likely that a modified form, or perhaps a different model altogether, could prove superior (at least with regard to scheduling effectiveness and the various deviation factors) to the analysis summaries.

Another factor which is significant from a long term viewpoint is the currently observed proliferation of computers within the American society in general. It is likely that future Air Force maintenance organizations will have the capability of performing simulation studies at the local level. If this occurs, a model such as the one developed here may become an important management tool. This would require, however, that the data base used by the simulation be as accurate as possible.

Recommendations

1. If maintenance dispatch data is to be used as source data for simulation purposes, then the accuracy and descriptive content of individual data entries will be critical. It is therefore recommended that the reasons for deviations be recorded in enough detail to pinpoint their exact cause.

For example, was a higher priority maintenance deviation due to not enough maintenance teams to handle the

additional dispatch requirement, or was there merely a shortage of equipment? This would also provide more substantive, quantitative information should manpower/equipment level increases be requested.

2. Modify the model developed here so that it uses a lower (i.e., less aggregate) level of data and rerun this simulation. For example, consider only dispatch deviations, or workorder deviations, for an individual type of team. This would yield a dispatch deviation rate or scheduling effectiveness rate for a selected segment of the SES.

Summary

This research has examined the Minuteman Missile Maintenance Schedule Execution System. The primary thrust here has been toward the development of a management tool that could enhance a manager's ability to favorably control the maintenance scheduling effectiveness rate. It is the contention of this study that higher scheduling effectiveness rates are both achievable and desirable, and that finite managerial resources should be directed toward those areas which provide the greatest increase in the scheduling effectiveness rate.

In order to effectively employ managerial resources, the manager must first discover those areas which are susceptible to improvement efforts, and then evaluate the effects of these efforts.

The evaluation step is difficult however, and misapplication of resources in the real system can be costly. On the other hand, a computer simulation, if it closely replicates the real world situation, can provide a manager with much needed insight into the situation without the attendant, adverse consequences caused by a "wrong" decision.

Given the above mentioned conditions, it is the authors' contention that computer simulation, and other mathematical techniques not presented here could enhance the maintenance effort if they are intelligently applied. It is therefore hoped that this research has provided a springboard for future studies in this area, and will help current and future maintenance managers be both more effective and more efficient.

APPENDIX A

Q-GERT PROGRAM AND USER FUNCTION FOR
GENERATING MODIFIED EXPONENTIAL
VARIATES FOR THE PERS VARIABLE

```

LI,PERGEN
1 $JOB,EXGEN,2081LSMS,NCA384,OUTPUT=16
2 AS,73=EXTEST
3 QBERT.UL,,BAGEN
4 GEN,EXGEN,THESES.6,22,1982,,1,1,,1,(20)E4*
5 SOU,1,0,1,D,M*
6 ACT,1,2,UF,1*
7 SIN,2,1,1,,I*
8 PAR,1,2.116,0.,10.*
9 FIN*
EOF..
EOT..

```

```

LI,BAGEN
1      FUNCTION UF(IFN)
2      COMMON/QUAR/NDE,NFTBU(100),NREL(100),NREL2(100),NRUN,
3      *NRUNS,NTC(100),PARAM(100,4),TBEG,TNOU/USER/NDAY(121),I
4      DATA NDAY,I/122*0/
5      GO TO (1),IFN
6 1     UF=0.0
7      DO 10 I=1,121
8          SAMP=EX(I)
9          NDAY(I)=SAMP+.5
10         WRITE (73,100) I,NDAY(I)
11 10    CONTINUE
12 100   FORMAT(1X,I3,3X,I5)
13      RETURN
14      END
EOF..
EOT..

```

APPENDIX B

Q-GERT PROGRAM AND USER FUNCTION FOR
GENERATING MODIFIED EXPONENTIAL
VARIATES FOR THE UNC VARIABLE

```

LI,EXGEN
1  $JOB,EXGEN,2081LSHS,MCA384,OUTPUT=16
2  AS,73=EXTEST
3  QGERT.UL,,UNCGEN
4  GEN,EXGEN,THESIS,6,22,1982,,1,1,,1,(20)E4*
5  SOU,1,0,1,0,M*
6  ACT,1,2,UF,1*
7  SIN,2,1,1,,1*
8  PAR,1,4.124,0.,16.*
9  FIN*
EOF..
EOT..

```

```

LI,UNCGEN
1  FUNCTION UF(IFN)
2  COMMON/QUAR/NDE,NFTBU(100),NREL(100),NREL1(100),NREL2(100),NRUN,
3  +NRUNS,NTC(100),PARAM(100,4),TBEG,TNOU/USER/NDAY(121),I
4  DATA NDAY,I/122*0/
5  GO TO (1),IFN
6 1  UF=0.0
7  DO 10 I=1,121
8  SAMP=EX(I)
9  NDAY(I)=SAMP
10 WRITE (73,100) I,NDAY(I)
11 10 CONTINUE
12 100 FORMAT(1X,I3,3X,I5)
13 RETURN
14 END
EOF..
EOT..

```

APPENDIX C

Q-GERT PROGRAM AND USER FUNCTION
USED TO SIMULATE THE SCHEDULE
EXECUTION SYSTEM

LI,MDBERT
 1 \$JOB,LAST1,2001LSMS,MCA3B4,OUTPUT=86
 2 AS,71=POL2
 3 AS,72=RESLT9
 4 QGERT,UL,,MDFUNC
 5 GEN,VACHAC,THESIS,3,9,1982,,1,363,,1,,6,(20)E4*
 6 SOU,1,0,1,D,M*
 7 REQ,2,1,1,D*
 8 REQ,3,1,1,D*
 9 REQ,4,1,1,D*
 10 SIN,5,1,1,,I*
 11 ACT,1,2,CO,0*
 12 ACT,2,3,CO,0*
 13 ACT,3,4,CO,0*
 14 ACT,4,5,CO,0*
 15 ACT,4,1,CO,1*
 16 VAS,1,1,NO,1,2,IN,1*
 17 VAS,2,3,UF,1,1-,AT,3*
 18 VAS,3,4,UF,2,1-,AT,4*
 19 VAS,4,5,UF,3,1-,AT,5,4,UF,4*
 20 PAR,1,41.537,6.,91.,15.909*
 21 FIN*
 EOF..
 EOT..

L1,NBFUNC

```

1  FUNCTION UF(IFN)
2  INTEGER AT2,I
3  COMMON/OVAR/NDE,NFTBU(100),NREL(100),NREL2(100),NRUN,
4  +NRUNS,NTC(100),PARAM(100,4),TDEB,THOW/USER/TSCH,TCOMP,DSCH(363),
5  +DCOMP(363),DBEF(363),TSEF,J,CPPI(5),VALP1(5),CPP2(8),VALP2(8),
6  +CPP3(10),VALP3(10),CPP4(7),VALP4(7),CPU1(5),VALU1(5),CPU2(9),
7  +VALU2(9),CPU3(13),VALU3(13),CPU4(9),VALU4(9),CPVE1(2),VALVE1(2),
8  +CPVE2(3),VALVE2(3),CPVE3(6),VALVE3(6),CPVE4(4),VALVE4(4)
9  DATA DSCH,DCOMP,DBEF,TSCH,TCOMP,TSEF,J,I/1092+0.0,2+0/
10 DATA CPP1/.55,.7,.8,.85,1.0/
11 DATA VALP1/0.0,1.0,2.0,3.0,4.0/
12 DATA CPP2/.175,.4,.675,.775,.85,.925,.95,1.0/
13 DATA VALP2/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0/
14 DATA CPP3/.044,.155,.444,.622,.755,.844,.933,.955,.977,1.0/
15 DATA VALP3/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,10.0,11.0/
16 DATA CPP4/.0625,.25,.5,.625,.75,.9375,1.0/
17 DATA VALP4/0.0,1.0,2.0,3.0,4.0,5.0,8.0/
18 DATA CPU1/.35,.7,.9,.95,1.0/
19 DATA VALU1/0.0,1.0,2.0,3.0,4.0/
20 DATA CPU2/.175,.425,.65,.75,.8,.825,.85,.925,1.0/
21 DATA VALU2/0.0,1.0,2.0,3.0,5.0,6.0,7.0,8.0,9.0/
22 DATA CPU3/.156,.333,.467,.533,.689,.756,.8,.867,.889,.911,.956,
23 +.978,1.0/
24 DATA VALU3/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,9.0,10.0,11.0,
25 +14.0,15.0/
26 DATA CPU4/.188,.375,.5,.625,.75,.813,.875,.938,1.0/
27 DATA VALU4/2.0,3.0,5.0,8.0,10.0,12.0,13.0,14.0,15.0/
28 DATA CPVE1/.95,1.0/
29 DATA VALVE1/0.0,1.0/
30 DATA CPVE2/.75,.925,1.0/
31 DATA VALVE2/0.0,1.0,2.0/
32 DATA CPVE3/.733,.844,.933,.955,.977,1.0/
33 DATA VALVE3/0.0,1.0,2.0,3.0,4.0,6.0/
34 DATA CPVE4/.6875,.875,.9375,1.0/
35 DATA VALVE4/0.0,1.0,3.0,6.0/
36 GO TO (1,2,3,4),IFN
37 1 UF=0.0
38 AT1=BATR(1)
39 AT2=BATR(2)
40 J=AT1+.5
41 DSCH(AT2)=J
42 TSCH=TSCH+J
43 IF(J.LE. 25) THEN
44     SAMPP=DPROB(CPP1,VALP1,5,2)
45 ELSE IF((J.GE. 26).AND.(J.LE. 41)) THEN
46     SAMPP=DPROB(CPP2,VALP2,8,2)
47 ELSE IF((J.GE. 42).AND.(J.LE. 57)) THEN
48     SAMPP=DPROB(CPP3,VALP3,10,2)
49 ELSE
50     SAMPP=DPROB(CPP4,VALP4,7,2)
51 END IF
52 UF=SAMPP
53 RETURN

```

```

54 2      UF=0.0
55 C      ORIGINAL PLACEMENT FOR VEHICLE DEVIATION CALCULATION
56        UF=0.0
57        RETURN
58 3      UF=0.0
59        IF(J .LE. 25) THEN
60          SAMPV=DPROB(CPU1,VALU1,5,2)
61          SAMPV=DPROB(CPVE1,VALUE1,2,2)
62        ELSE IF((J .GE. 26) .AND. (J .LE. 41)) THEN
63          SAMPV=DPROB(CPU2,VALU2,9,2)
64          SAMPV=DPROB(CPVE2,VALUE2,3,2)
65        ELSE IF((J .GE. 42) .AND. (J .LE. 57)) THEN
66          SAMPV=DPROB(CPU3,VALU3,13,2)
67          SAMPV=DPROB(CPVE3,VALUE3,4,2)
68        ELSE
69          SAMPV=DPROB(CPU4,VALU4,9,2)
70          SAMPV=DPROB(CPVE4,VALUE4,4,2)
71        END IF
72        SAMPV=SAMPV+SAMPV
73        UF=SAMPV
74        RETURN
75 4      UF=0.0
76        AT1=GATRD(1)
77        N=AT1
78        DCOMP(AT2)=N
79        IF(DCOMP(AT2) .LE. 0) THEN
80          DSEF(AT2)=0.0
81        ELSE IF(DCOMP(AT2) .GE. DSCH(AT2)) THEN
82          DSEF(AT2)=100.0
83        ELSE
84          DSEF(AT2)=(DCOMP(AT2)/DSCH(AT2))*100
85        END IF
86        TCOMP=TCOMP+DCOMP(AT2)
87        RETURN
88        END

```

```

89      SUBROUTINE UO
90      INTEGER AT2
91      COMMON/QUAR/NDE,NFTBU(100),NREL(100),NREL2(100),NRUN,
92      +NRUNS,NTC(100),PARAM(100,4),TBEG,TNOW/USER/TSCH,TCOMP,DBSCH(363),
93      +DCOMP(363),DSEF(363),TSEF,J,CPP1(5),VALP1(5),CPP2(8),VALP2(8),
94      +CPP3(10),VALP3(10),CPP4(7),VALP4(7),CPU1(5),VALU1(5),CPU2(9),
95      +VALU2(9),CPU3(13),VALU3(13),CPU4(9),VALU4(9),CPVE1(2),VALUE1(2),
96      +CPVE2(3),VALUE2(3),CPVE3(6),VALUE3(6),CPVE4(4),VALUE4(4)
97      TSEF=(TCOMP/TSCH)*100
98      PRINT*, 'TOTAL WORKORDERS SCHEDULED= ',TSCH
99      PRINT*, 'TOTAL WORKORDERS COMPLETED= ',TCOMP
100     PRINT*, 'TOTAL SCHEDULING EFFECTIVENESS= ',TSEF
101     IF(NRUN.EQ. 1) THEN
102         DO 10 I=1,363
103             WRITE (72,101) DSEF(I),DCOMP(I),DBSCH(I)
104 10     CONTINUE
105     END IF
106     WRITE (71,100) TSEF
107 100   FORMAT(1X,F8.4)
108 101   FORMAT(1X,F8.4,2X,F8.4,2X,F8.4)
109     TSCH=0.0
110     TCOMP=0.0
111     RETURN
112     END
EOF..
EOT..

```

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